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Investigation on fretting wear behavior of 690 alloy in water under various temperatures

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ABSTRACT

The aim of this paper is to assess the effect of water temperature (room temperature – RT, 60 °C and 90 °C) on fretting wear behavior of 690 alloy tubes against 405 stainless steel plates, and compare it with fretting in dry condition. Due to the lubrication effect, the presence of a thin water film likely precluded the metal-metal contact, and resulted in less wear. During the fretting process, water also washed the wear particles away from the contact zone leading to a decrease of abrasive wear. Consequently, the wear scars showed "U" shape profile along the fretting direction in water, while "W" shape in air.

1. Introduction

Due to flow-induced vibration, steam generator tubes in pressurized water reactor are expected to be subject to small amplitude oscillatory motion against their supports (or anti-vibration bars) [1]. The value of oscillation frequency and relative displacement of steam generator tubes were reported to reach up to 30 Hz and 200 μm, respectively [2–3]. Moreover, the tubes are operated in such an aggressive condition at temperature up to 325 °C [4]. The need of understanding and predicting the failure of steam generator tubes attracts the attention of researchers, due to its significant economic and safety impacts. As alternative to Inconel 600 alloy, Inconel 690 alloy has recently been used as the material of steam generator tubes in nuclear plants [5]. This is mainly owing to its combined superior stress corrosion cracking resistance, and excellent mechanical characteristics at high temperature and in high pressure water. Although many detailed studies have been carried out on fretting fatigue [6–7], corrosion behavior [8–9] and stress corrosion cracking in simulated PWR primary water [10–12], they rarely revealed relevant information on fretting wear of Inconel 690 alloy in PWR secondary water. The fretting action possibly results in contact surfaces wear by detachment of particles, and contact fatigue by rapid crack nucleation and propagation, leading to premature catastrophic failures [13]. Hence, it was necessary to pay more attention to fretting wear of steam generator tubes.

More work was reported in the open literatures on the effect of various test conditions on wear in air [2,14–17], while less studies treated the fretting wear behaviors under wet condition. The work on fretting wear of 690 alloy for different level of pH environment have demonstrated that the friction coefficient reached the maximum at pH value of 7 due to different surface states at different pH values [18]. Zhang et al. found that abrasive wear and delamination were the main mechanisms of Inconel 690 in distilled water. When fretted in hydrazine solution, cracks accompanied by abrasive wear and delamination dominated wear mechanisms were observed [19]. To address the problem of fretting corrosion of heat exchanger tubes, ferritic–martensitic steel T91 and austenitic steel 1.4970 were tested in liquid lead. [3]. Most of fretting wear experiments were carried out using ball-on-plate [20–22] or ball-on-tube, and only very limited data are available on fretting wear of tube/plate contact configuration.

The present work, therefore, was initiated with the objective of generating relevant design data on the fretting wear behavior of 690 alloy tubes in simulated PWR secondary water, at different temperatures. The fretting wear tests were carried out for tube/plate contact configuration. To distinguish wear mechanisms, the worn surfaces and the morphology of cross-sections of the wear scars were observed through SEM, EDX and EPMA. Moreover, a particular debris cleaning method was used to remove wear particles of worn 690 alloy tube effectively in order to estimate exact wear volume [23].

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2. Experimental set-up

2.1. The test specimens

The specimens selected in this study were 690 alloy (*R*a=0.4 μm) and 405 stainless steel (*R*a=0.6 μm), that are widely used in nuclear industry – for generator tubes and anti-vibration bars, respectively. The microstructure of 690 alloy is presented in Fig. 1. The chemical composition and mechanical properties of the tested materials are listed in Tables 1 and 2, respectively. The details of configuration parameters of the test specimens were reported elsewhere [23]. 690 Alloy was cut from an as-received generator tube made by Baosteel. For each test samples had been ultrasonically cleaned in ethyl alcohol and then dried with hot compressed air, prior to being assembled on the tribometer.

2.2. Fretting wear test conditions

The experimental investigation was performed on a fretting wear test rig with a contact configuration of tube-on-plate, as shown in Fig. 2. The direction of motion was perpendicular to the axis of the tube. To achieve elevated temperature in water environment, the fretting wear tester was connected to a water supplying loop system in these experiments, special heaters were used to heat the water supplied to the water tank through the IN hole. The water left through the OUT hole on the opposite side in order to maintain the water level. The tribological tests have been carried out in water at various temperature of RT (room temperature), 60 °C and 90 °C, with a deviation of ±2%. The displacement amplitudes of fretting wear were controlled at 100 μm and 200 μm. Other parameters were kept unchanged for all tests; a frequency of 5 Hz, 10^5 fretting cycles and a normal load of 40 N (equivalent to a maximal Hertz contact stress of 23.074 MPa). In this work, the test solution was simulated PWR secondary water (deionized water mixed with few ammonia water). The pH of the test solution was 9.0–9.1 at RT, and the conductance was approximately 3.0. For the sake of simplicify, the solution environment will be referred to as the water environment in this paper.

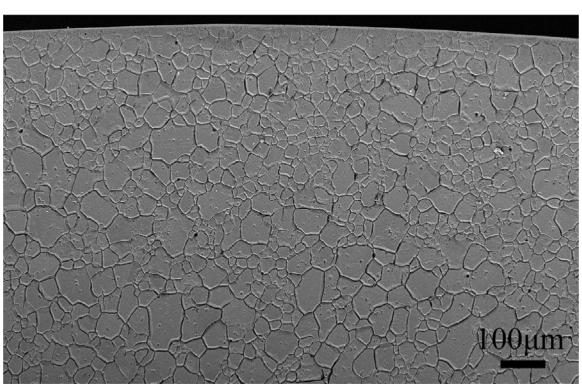

Fig. 1. Mircostructure of 690 alloy.

2.3. Surface analysis

After the fretting wear tests, in order to reveal the wear mechanisms, the specimens were examined using SEM, EDX and EPMA to obtain information of morphologies and surface chemical compositions. Subsequently, a 3D optical microscope (Bruker ContourGT-I) was used to acquire the profile of the wear scars. Following the wear scar morphology examination and surface chemical analysis, the specimens were cleaned through a special chemistry cleaning method (APAC) to remove wear debris. Finally, the wear volume was measured again using a 3D optical microscope. The cleaning steps of APAC consisted of four steps. After cleaned with ethyl alcohol ultrasonically, specimens were put into, successively, approximately boiling mixture of permanganate and sodium hydroxide, and the solution of citric acid diammonium hydrogen. Finally, specimens were cleaned by ultrasonication in ethyl alcohol and then dried with the hot compressed air.

3. Results

3.1. F_t–*D* curves and friction coefficient

As shown in Fig. 3, the shape of all the F_t–*D* plots to be close to parallelogram, indicating that all the tests were in the running state of gross slip, *i.e.* in the gross slip regime. The gross slip generally resulted in larger amounts of material removal and debris formation. In Fig. 3, the initial friction force was relatively low and reached a peak around 10,000 cycles above 60 °C.

As indicated in Fig. 4, the values of friction coefficients were about 0.4 at the end of the tests in water at various temperatures. However the friction coefficient curves presented very different

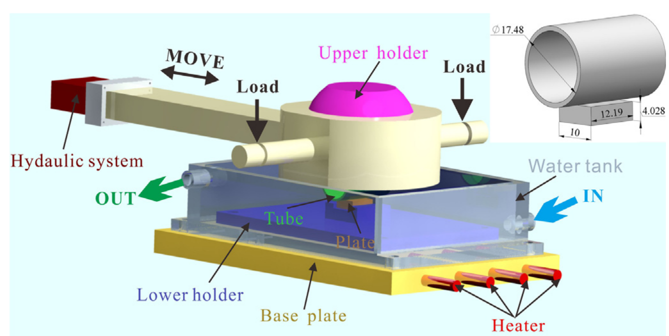

Fig. 2. Schematic diagram of fretting wear tester.

Table 2
Mechanical properties of 690 alloy and 405 stainless steel.

Mechanical properties	Hardness (HB)	Yield strength (MPa)	Elasticity modulus (GPa)
690 Alloy	–	336.5	208
405 Stainless	160	373	201

Table 1
Chemical composition of 690 alloy and 405 stainless steel.

Chemical composition	Ni	Cr	Fe	Al	C	Si	Mn	S	P
690 Alloy	≥58.0	28.5–31.0	9.0–11.0	≤0.40	0.015–0.025	≤0.50	≤0.50	≤0.003	≤0.015
405 Stainless	≤0.60	11.5–14.5	Bal.	0.10–0.30	≤0.08	≤1.00	≤1.00	≤0.030	≤0.040

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